1

Dynamical Downscaling of Projected 21st Century Climate for the Carpathian Basin

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1. Introduction

According to the Working Group I contributions (Solomon et al., 2007) to the Fourth Assessment Report of the Intergovermental Panel on Climate Change (IPCC), the key processes influencing the European climate include increased meridional transport of water vapour, modified atmospheric circulation, reduced winter snow cover (especially, in the northeastern regions), more frequent and more intense dry conditions of soil in summer in the Mediterranean and central European regions. Future projections of IPCC for Europe suggest that the annual mean temperature increase will likely to exceed the global warming rate in the 21st century. The largest increase is expected in winter in northern Europe (Benestad, 2005), and in summer in the Mediterranean area. Minimum temperatures in winter are very likely to increase more than the mean winter temperature in northern Europe (Hanssen-Bauer et al., 2005), while maximum temperatures in summer are likely to increase more than the mean summer temperature in southern and central Europe (Tebaldi et al., 2006). Concerning precipitation, the annual sum is very likely to increase in northern Europe (Hanssen-Bauer et al., 2005) and decrease in the Mediterranean area. On the other hand, in central Europe, which is located at the boundary of these large regions, precipitation is likely to increase in winter, while decrease in summer. In case of the summer drought events, the risk is likely to increase in central Europe and in the Mediterranean area due to projected decrease of summer precipitation and increase of spring evaporation (Pal et al., 2004; Christensen & Christensen, 2004). As a consequence of the European warming, the length of the snow season and the accumulated snow depth are very likely to decrease over the entire continent (Solomon et al., 2007).
Coarse spatial resolution of global climate models (GCMs) is inappropriate to describe regional climate processes; therefore, GCM outputs of typically 100-300 km may be misleading to compose regional climate change scenarios for the 21st century (Mearns et al., 2001). In order to determine better estimations of regional climate conditions, fine resolution regional climate models (RCMs) are widely used. RCMs are limited area models nested in GCMs, i.e., the initial and the boundary conditions of RCMs are provided by the GCM outputs (Giorgi, 1990). Due to computational constrains the domain of an RCM evidently does not cover the entire globe, and sometimes not even a continent. On the other hand, their horizontal resolution may be as fine as 5-10 km.
In Europe, the very first comprehensive and coordinated effort for providing RCM projections was the project PRUDENCE (Prediction of Regional scenarios and Uncertainties

for Defining EuropeaN Climate change risks and Effects), which involved 21 European research institutes and universities (Christensen, 2005). The primary objectives of PRUDENCE were (i) to provide 50 km horizontal resolution climate change scenarios for Europe for 2071-2100 using dynamical downscaling methods with RCMs (compared to 1961-1990 as the reference period), and (ii) to explore the uncertainty in these projections considering the applied emission scenario (IPCC SRES A2 and B2), the boundary conditions (using HadAM3H, ECHAM4, and ARPEGE as the driving GCM), and the regional model (Christensen et al., 2007). Results of the project PRUDENCE are disseminated widely via Internet (http://prudence.dmi.dk), thus supporting socio-economic and policy related decisions.

In smaller regions such as the Carpathian Basin (located in Eastern/Central Europe), 50 km horizontal resolution may still not be appropriate to describe the meso-scale processes (e.g., cloud formation and convective precipitation). For this purpose on a national level several RCMs have been adapted with finer resolution (25 and 10 km). Here, results from two of the adapted RCMs for Hungary are analyzed, namely, models PRECIS and RegCM.

In this paper, first, data and models from PRUDENCE, PRECIS and RegCM are presented. Then, the regional climate change projections are summarized for the Carpathian Basin using the outputs of the available simulations. Results of the projected mean temperature and precipitation change by the end of the 21st century are discussed using composite maps. Furthermore, the simulated changes of the extreme climate indices following the guidelines suggested by one of the task groups of a joint WMO-CCl (World Meteorological Organization Commission for Climatology) – CLIVAR (a project of the World Climate Research Programme addressing Climate Variability and Predictability) Working Group formed in 1998 on climate change detection (Karl et al., 1999; Peterson et al., 2002) are also analyzed.

2. Data, models

The RCMs nested into GCM are used to improve the regional climate change scenarios for the European subregions. For analyzing the possible regional climate change in the Carpathian Basin, we analyzed PRUDENCE outputs, and have adapted the models PRECIS and RegCM at the Department of Meteorology, Eötvös Loránd University.

For assessing the future conditions, three emission scenarios are considered in this paper, namely, SRES A2, A1B, and B2 (Nakicenovic & Swart, 2000). According to the A2 global emission scenario, fertility patterns across regions converge very slowly resulting in continuously increasing world population. Economic development is primarily regionally oriented, per capita economic growth and technological changes are fragmented and slow. The projected CO_2 concentration may reach 850 ppm by the end of the 21st century (Nakicenovic & Swart, 2000), which is about triple of the pre-industrial concentration level (280 ppm). The global emission scenario B2 describes a world with intermediate population and economic growth, emphasizing local solutions to economic, social, and environmental sustainability. According to the B2 scenario, the projected CO_2 concentration is likely to exceed 600 ppm (Nakicenovic & Swart, 2000), which is somewhat larger than a double concentration level relative to the pre-industrial CO_2 conditions. A1B emission scenario estimates the CO_2 level reaching 717 ppm by 2100, which is an intermediate level considering all the three applied scenarios.

2.1 PRUDENCE outputs

16 experiments from the PRUDENCE simulations considered the IPCC SRES A2 emission scenario (Nakicenovic & Swart, 2000), while only 8 experiments used the B2 scenario (Table 1). Most of the PRUDENCE simulations (Déqué et al., 2005) used HadAM3H/HadCM3 (Gordon et al., 2000; Rowell, 2005) of the UK Met Office as the driving GCM. Only a few of them used ECHAM4 (Roeckner et al., 2006) or ARPEGE (Déqué et al., 1998). Simulated temperature and precipitation outputs were separated and downloaded (from the data server at http://prudence.dmi.dk) for the region covering the Carpathian Basin (45.25°-49.25°N, 13.75°-26.50°E).

Institute	RCM	Driving GCM	Scenario
Danish Meteorological Institute	HIRHAM	HadAM3H/HadCM3	A2, B2
Hadley Centre of the UK Met Office	HadRM3P	HadAM3H/HadCM3	A2, B2
ETH (Eidgenössische Technische Hochschule)	CHRM	HadAM3H/HadCM3	A2
GKSS (Gesellschaft für Kernenergieverwertung in Schiffbau und Schiffahrt)	CLM	HadAM3H/HadCM3	A2
Max Planck Institute	REMO	HadAM3H/HadCM3	A2
Swedish Meteorological and Hydrological Institute	RCAO	HadAM3H/HadCM3 ECHAM4/OPYC	A2, B2 B2
UCM (Universidad Complutense Madrid)	PROMES	HadAM3H/HadCM3	A2,B2
International Centre for Theoretical Physics	RegCM	HadAM3H/HadCM3	A2, B2
Norwegian Meteorological Institute	HIRHAM	HadAM3H/HadCM3	A2
KNMI (Koninklijk Nederlands Meteorologisch Institute)	RACMO	HadAM3H/HadCM3	A2
Météo-France	ARPEGE	HadAM3H/HadCM3 ARPEGE/OPA	A2, B2 B2

Table 1. List of the PRUDENCE RCMs used in this analysis

2.2 Model PRECIS

The model PRECIS is a high resolution limited area model (HadRM3P) with both atmospheric and land surface modules. The model was developed at the Hadley Climate Centre of the UK Met Office (Wilson et al., 2007), and it can be used over any part of the globe (e.g., Hudson and Jones, 2002, Rupa Kumar et al., 2006, Taylor et al., 2007, Akhtar et al., 2008). PRECIS is based on the atmospheric component of HadCM3 (Gordon et al., 2000) with substantial modifications to the model physics (Jones et al., 2004). The atmospheric component of PRECIS is a hydrostatic version of the full primitive equations, and it applies a regular latitude-longitude grid in the horizontal and a hybrid vertical coordinate. The horizontal resolution can be set to 0.44°×0.44° or 0.22°×0.22°, which gives a resolution of ~50 km or ~25 km, respectively, at the equator of the rotated grid (Jones et al., 2004). In our studies, we used 25 km horizontal resolution for modeling the Central European climate. Hence, the target region contains 123x96 grid points. There are 19 vertical levels in the model, the lowest at ~50 m and the highest at 0.5 hPa (Cullen, 1993) with terrain-following σ-coordinates (σ = pressure/surface pressure) used for the bottom four levels, pressure coordinates used for the top three levels, and a combination in between (Simmons and Burridge, 1981). The model equations are solved in spherical polar coordinates and the latitude-longitude grid is rotated so that the equator lies inside the region of interest in order to obtain quasi-uniform grid box area throughout the region. An Arakawa B grid (Arakawa and Lamb, 1977) is used for horizontal discretization to improve the accuracy of the split-explicit finite difference scheme. Due to its fine resolution, the model requires a time step of 5 minutes to maintain numerical stability (Jones et al., 2004).

In case of the control period (1961-1990), the initial and the lateral boundary conditions for the regional model are taken from (i) the ERA-40 reanalysis database (Uppala et al., 2005) using 1° horizontal resolution, compiled by the European Centre for Medium-range Weather Forecasts (ECMWF), and (ii) the HadCM3 ocean-atmosphere coupled GCM using ~150 km as a horizontal resolution. For the validation of the PRECIS results CRU TS 1.2 (Mitchell & Jones, 2005) datasets were used. According to the simulation outputs, PRECIS is able to sufficiently reconstruct the climate of the reference period in the Carpathian Basin (Bartholy et al., 2009a, 2009b). The temperature bias (i.e., difference between simulated and observed annual and seasonal mean temperature) is found mostly within (–1 °C; +1 °C) interval. The largest bias values are found in summer, when the average overestimation of PRECIS over Hungary is 2.2 °C.

Both spatial and temporal variability of precipitation is much larger than temperature variability. The spatially averaged precipitation is overestimated in the entire model domain, especially, in spring and winter (by 22% and 15%, respectively). The precipitation of the high-elevated regions is overestimated (by more than 30 mm in each season). The overestimation of the seasonal precipitation occurring in the plain regions is much less in spring than in the mountains (Bartholy et al., 2009c). On the other hand, the summer and autumn mean precipitation amounts are underestimated in the lowlands. The underestimation is larger in the southern subregions than in the northern part of the domain. Inside the area of Hungary the seasonal means are slightly underestimated (by less than 10% on average), except spring when it is overestimated by 35% on average. The spring bias values are significantly large in most of the gridpoints located inside the Hungarian borders.

Nevertheless, temperature and precipitation bias fields of the PRECIS simulations can be considered acceptable if compared to other European RCM simulations (Jacob et al., 2007, Bartholy et al., 2007). Therefore, model PRECIS can be used to estimate future climatic change of the Carpathian Basin. For the 2071-2100 future period, two experiments were completed (considering A2 and B2 global emission scenarios). Moreover, a transient model run for 1951-2100 have been accomplished using A1B scenario.

2.3 Model RegCM

Model RegCM is a 3-dimensional, σ-coordinate, primitive equation model, which was originally developed by Giorgi et al. (1993a, 1993b) and then modified, improved, and discussed by Giorgi & Mearns (1999) and Pal et al. (2000). The RegCM model (version 3.1) is available from the Abdus Salam International Centre for Theoretical Physics (ICTP). The dynamical core of the RegCM3 is fundamentally equivalent to the hydrostatic version of the NCAR/Pennsylvania State University mesoscale model MM5 (Grell et al., 1994). Surface processes are represented in the model using the Biosphere-Atmosphere Transfer Scheme, BATS (Dickinson et al., 1993). The non-local vertical diffusion scheme of Holtslag et al. (1990) is used to calculate the boundary layer physics. In addition, the physical parametrization is mostly based on the comprehensive radiative transfer package of the

NCAR Community Climate Model, CCM3 (Kiehl et al., 1996). The mass flux cumulus cloud scheme of Grell (1993) is used to represent the convective precipitation with two possible closures: Arakawa & Schubert (1974) and Fristch & Chappell (1980).
Model RegCM can use initial and lateral boundary conditions from global analysis dataset, the output of a GCM or the output of a previous RegCM simulation. In our experiments these driving datasets are compiled from the ECMWF ERA-40 reanalysis database (Uppala et al., 2005) using 1° horizontal resolution, and in case of scenario runs (for 3 time slices: 1961-1990, 2021-2050, and 2071-2100) the ECHAM5 GCM using 1.25° spatial resolution (Roeckner et al., 2006). The selected model domain covers Central/Eastern Europe centering at 47.5°N, 18.5°E and contains 120x100 grid points with 10 km grid spacing and 18 vertical levels. The target region is the Carpathian Basin with the 45.15°N, 13.35°E southwestern corner and 49.75°N, 23.55°E northeastern corner (Torma et al., 2008).
Validation of RegCM for the selected domain is discussed by Bartholy et al. (2009c) and Torma et al. (2011). Temperature is overestimated in winter (by 1.1 °C), and underestimated in the other seasons (by 0.3 °C, 0.2 °C, and 0.1 °C in spring, summer, and autumn, respectively). The largest bias values are identified in the high mountainous regions (Alps, southern part of the Carpathians). For Hungary, the seasonal bias values are +1.3 °C, –0.5 °C, –0.5 °C, and –0.2 °C for DJF, MAM, JJA, SON, respectively. The annual bias is less than 0.05 °C for the average of the Hungarian grid points. Precipitation is overestimated by 35% in winter, 25% in spring, 5% in summer, and 3% in autumn (on average for the whole domain). Persistent drying bias occurred in the southern part of the Alps. For Hungary, the seasonal bias values are acceptable and less than 23% (except in spring, when it is 29%). The annual bias is +16% for the Hungarian grid points on average.

3. Projected changes of the mean climate

In order to estimate the future climatic conditions of the Carpathian Basin, composite maps of projected temperature and precipitation change are shown. Furthermore, seasonal spatial averages of projected climate change are summarized for all the grid points located in Hungary.

3.1 Temperature

The projected seasonal temperature changes for A2 and B2 scenarios are shown in Fig. 1 (left and right panel, respectively) using RCM outputs of the PRUDENCE database. Similarly to the global and the European climate change results, larger warming is estimated for A2 scenario in the Carpathian Basin than for B2 scenario. The largest temperature increase is likely to occur in summer for both scenarios, the interval of the projected increase for the Hungarian grid points is 4.5-5.1 °C (A2 scenario) and 3.7-4.2 °C (B2 scenario). The smallest seasonal increase is simulated in spring, when the projected temperature increase inside Hungary is 2.8-3.3 °C for A2 and 2.3-2.7 °C for B2 scenario.
In addition to the PRUDENCE results, PRECIS and RegCM simulations are also included in Table 2. Projected seasonal mean temperature increases by the late 21st century are calculated for the grid points located in Hungary, and can be compared. Overall, the largest and the smallest warmings are projected for summer and for spring, respectively.

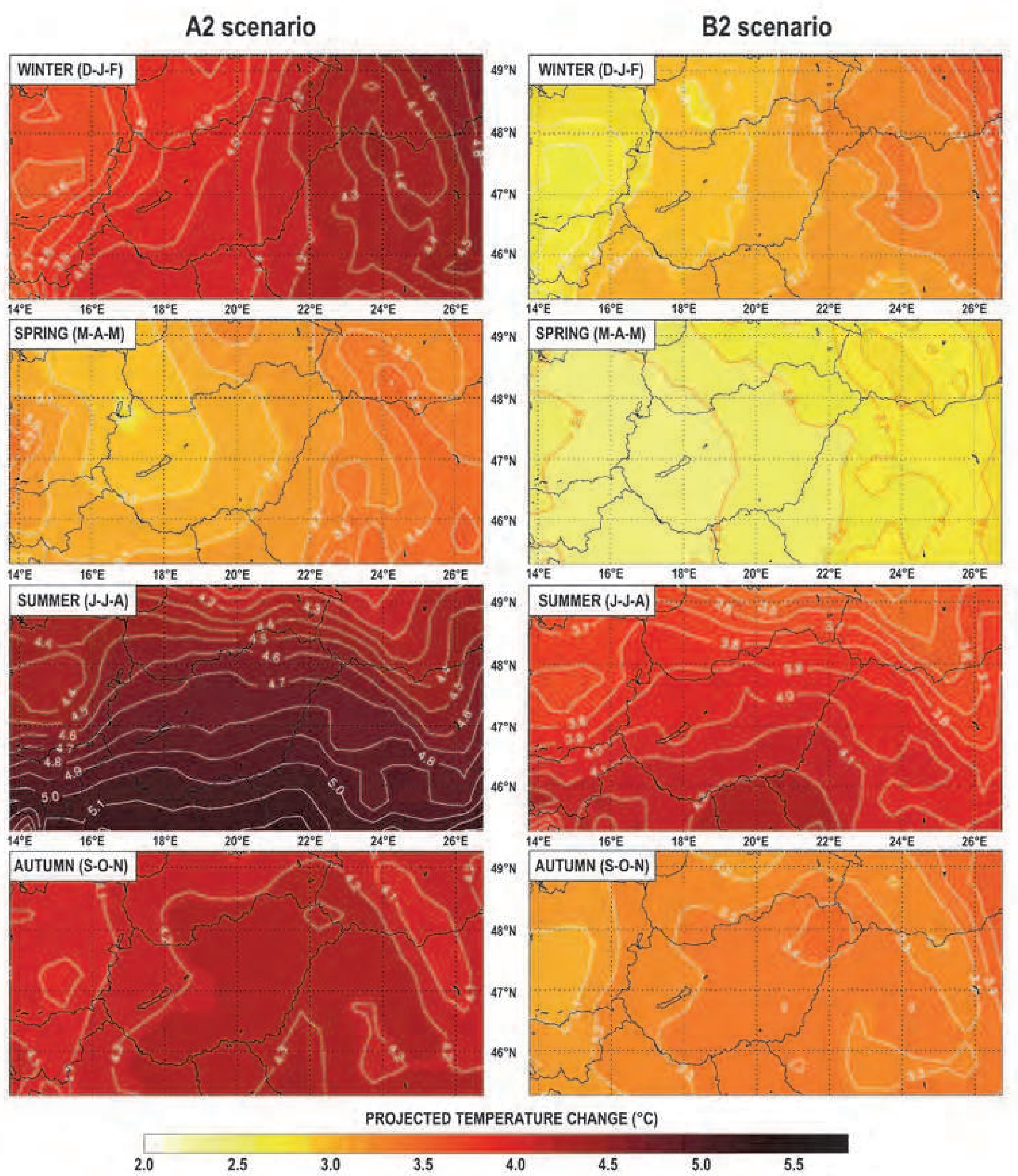

Fig. 1. Seasonal temperature change (°C) projected by 2071-2100 for the Carpathian Basin using the outputs of 16 and 8 PRUDENCE RCM simulations in case of A2 and B2 scenarios, respectively. (Reference period: 1961-1990)

Fig. 2 summarizes the projected mean seasonal warming for Hungary using the daily mean temperature simulations, as well, as the daily minimum and maximum temperature values. In general, the estimated warming by 2071-2100 is more than 2.4 °C and less than 5.1 °C for all seasons and for both scenarios.

RCM	Scenario	Winter	Spring	Summer	Autumn
PRUDENCE-composites	A2	4.0	3.1	4.8	4.2
PRECIS	A2	4.2	4.2	8.0	5.2
PRUDENCE-composites	B2	3.0	2.5	4.0	3.3
PRECIS	B2	3.2	3.1	6.0	3.9
PRECIS	A1B	4.2	3.7	6.7	5.0
RegCM	A1B	2.9	2.8	3.5	3.0

Table 2. Projected seasonal average warming (°C) for Hungary by 2071-2100 (reference period: 1961-1990)

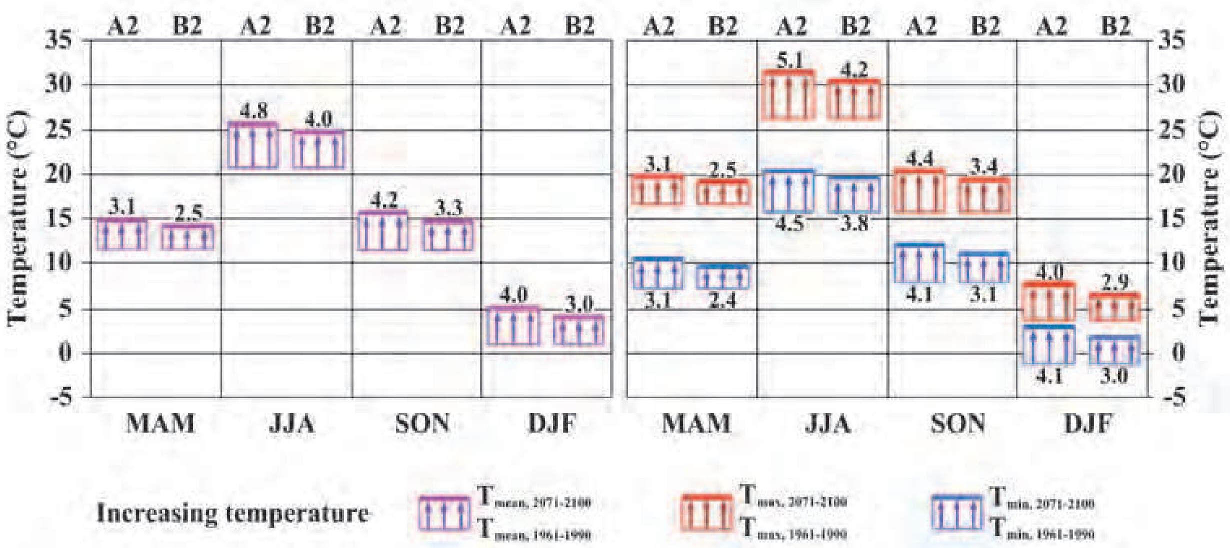

Fig. 2. Projected seasonal increase of daily mean, minimum and maximum temperature (°C) for Hungary using PRUDENCE outputs (temperature values of the reference period, 1961-1990, represent the seasonal mean temperature in Budapest on the basis of observations)

Projected temperature changes for the A2 scenario are larger than for the B2 scenarios in case of all the three temperature parameters. The smallest difference is estimated in spring (0.6-0.7 °C), and the largest in winter (1.0-1.1 °C). The largest daily mean temperature increase is projected in summer, 4.8 °C (A2) and 4.0 °C (B2), and the smallest in spring (3.1 °C for A2 and 2.5 °C for B2 scenario). Estimated increase of the daily maximum temperature exceeds that of the daily minimum temperature by about 0.1-0.6 °C (the largest is in summer). The only exception is in winter when the seasonal average daily minimum temperature is projected to increase by 4.1 °C (considering the A2 scenario) and 3.0 °C (considering the B2 scenario) – both of them are 0.1 °C larger than what is projected for the daily maximum temperature increase. The seasonal standard deviation fields (Bartholy et al., 2007) suggest that the largest uncertainty of the estimated temperature change occurs in summer for both emission scenarios.

3.2 Precipitation

Similarly to temperature projections, composites of mean seasonal precipitation change and standard deviations are mapped for both A2 and B2 scenarios for the 2071-2100 period. Fig. 3 presents the projected seasonal precipitation change for A2 and B2 scenarios (left and right panel, respectively) for the Carpathian Basin. The annual precipitation sum is not expected to change significantly in this region (Bartholy et al., 2003), but it is not valid for seasonal precipitation. According to the results shown in Fig. 3, summer precipitation is very likely to decrease in Hungary by 24-33% (A2 scenario) and 10-20% (B2 scenario). Winter precipitation in Hungary is likely to increase considerably by 23-37% and 20-27% using A2 and B2 scenarios, respectively. Moreover, slight decrease of autumn and slight increase of spring precipitation are also projected, however, neither of them is significant. Based on the seasonal standard deviation values (Bartholy et al., 2007), the largest uncertainty of precipitation change is estimated in summer, especially, in case of A2 scenario (when the standard deviation of the RCM results exceeds 20%).

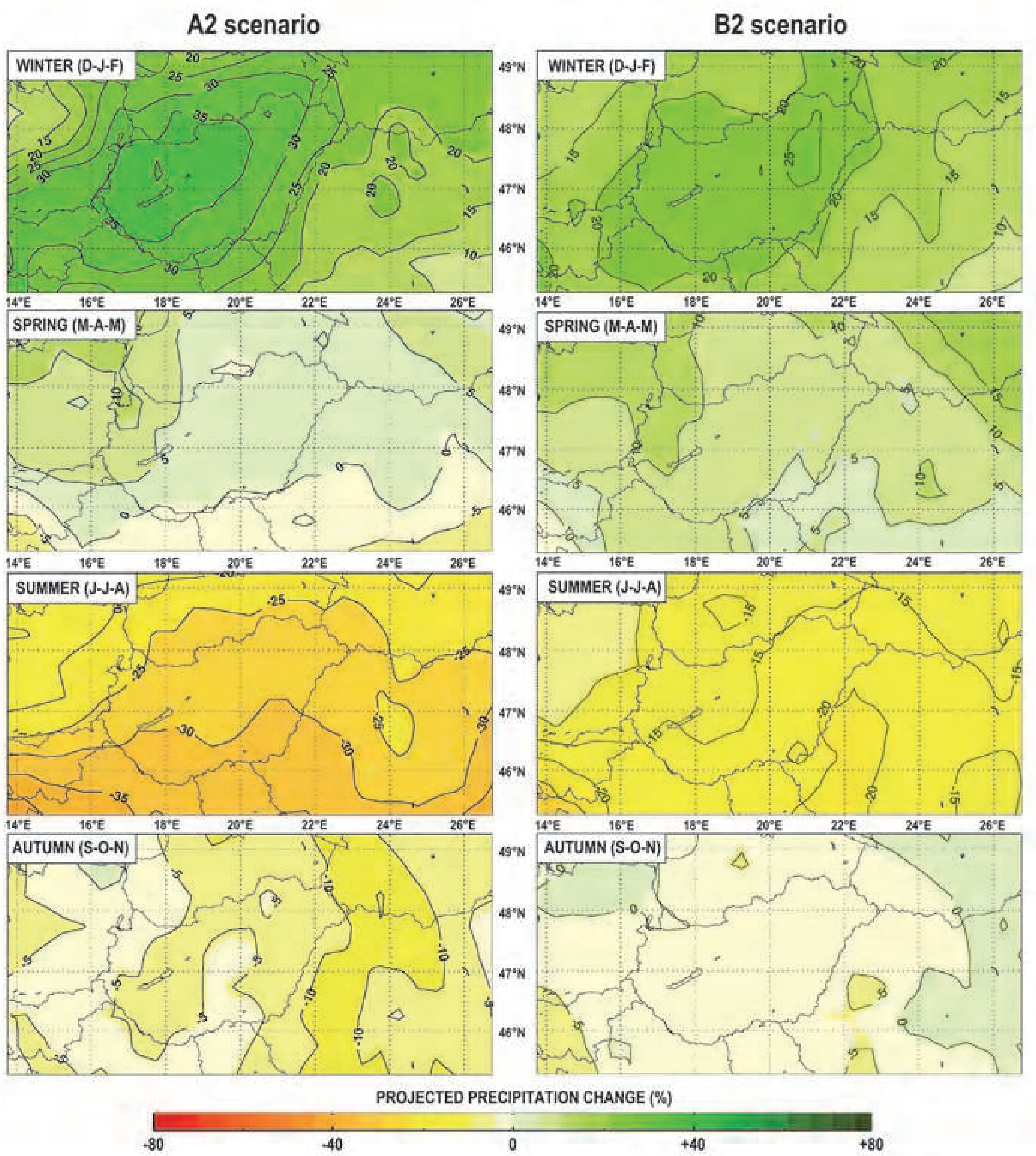

Fig. 3. Seasonal precipitation change (%) projected by 2071-2100 for the Carpathian Basin using the outputs of 16 and 8 PRUDENCE RCM simulations in case of A2 and B2 scenarios, respectively. (Reference period: 1961-1990)

Estimated seasonal mean precipitation changes by 2071-2100 on the basis of PRUDENCE results are compared to PRECIS and RegCM simulations in Table 3. The average percentage of precipitation changes are determined considering the grid points located in Hungary. Overall, different sources agree on the summer drying tendencies. Increase of precipitation in winter is also very likely in the future. Projected changes for spring and autumn are smaller than projections for the solstice seasons. Moreover, different RCMs often estimate changes to opposite direction, which highlights the large uncertainty associated to these precipitation projections.

RCM	Scenario	Winter	Spring	Summer	Autumn
PRUDENCE-composites	A2	+32	+5	-29	-7
PRECIS	A2	+14	-13	-58	-8
PRUDENCE-composites	B2	+24	+8	-15	-3
PRECIS	B2	-6	-8	-43	-18
PRECIS	A1B	+34	+5	-33	-4
RegCM	A1B	+8	-5	-18	+5

Table 3. Projected seasonal average precipitation change (%) for Hungary by 2071-2100 (reference period: 1961-1990)

The projected seasonal change of precipitation for Hungary in case of A2 and B2 scenarios are summarized in Fig. 4. Green and yellow arrows indicate increase and decrease of precipitation, respectively. According to the 1961-1990 reference period, the wettest season was summer, less precipitation was observed in spring, less in autumn, and the driest season was winter. If the projections are realized then the annual distribution of precipitation will be totally restructured, namely, the wettest seasons will be winter and spring (in this order) in cases of both A2 and B2 scenarios. The driest season will be summer in case of A2 scenario, while autumn in case of B2 scenario.

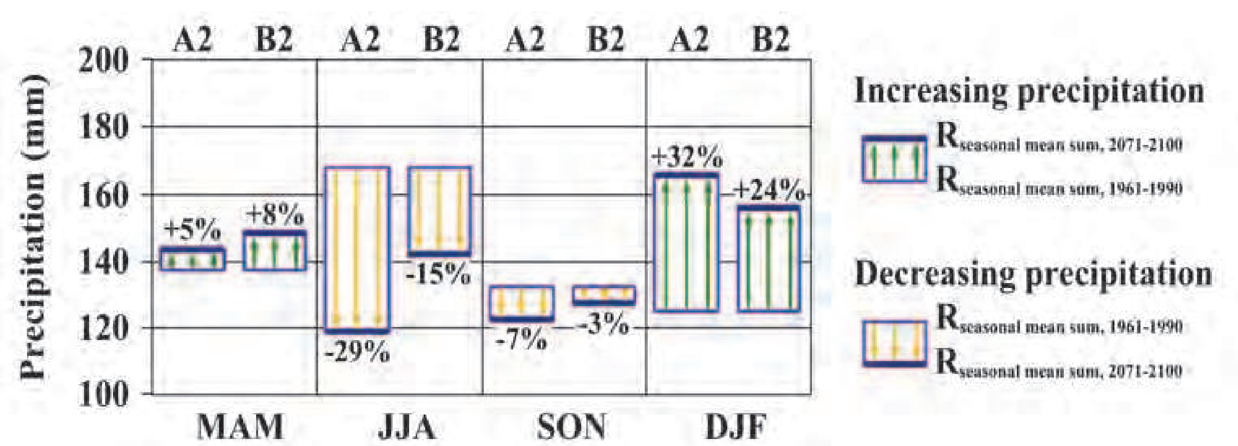

Fig. 4. Projected seasonal change of mean precipitation (mm) for Hungary using PRUDENCE outputs (increasing or decreasing precipitation is also indicated in %). Precipitation values of the reference period, 1961-1990, represent the seasonal mean precipitation amount in Budapest on the basis of observations.

On the base of the projections, the annual difference between the seasonal precipitation amounts is projected to decrease significantly (by half) in case of B2 scenario, which implies more similar seasonal amounts. The precipitation difference is not projected to change in case of A2 scenario, nevertheless, the wettest and the driest seasons will be completely changed.

4. Extremes

Regional analysis of the detected trend of different extreme climate indices for the Carpathian Basin is discussed by Bartholy & Pongrácz (2005, 2006, 2007) where the list and the definition of the indices can be found also. In this paper, the projected future trends of extreme climate indices are analyzed in the Carpathian Basin using daily temperature and precipitation outputs of four different PRUDENCE RCMs run by (i) the Danish Meteorological Institute (DMI), (ii) the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, (iii) the Royal Meteorological Institute of the Netherlands (Koninklijk Nederlands Meteorologisch Institute, KNMI), and (iv) the Swiss Federal Institute of Technology Zurich (Eidgenössische Technische Hochschule Zürich, ETHZ). For all of these simulations the boundary conditions were provided by the HadAM3H/HadCM3 (Table 1). DMI used the HIRHAM4 RCM (Christensen et al., 1996), which has been developed jointly by DMI and the Max-Planck Institute in Hamburg. ICTP used the regional climate model RegCM (Giorgi et al., 1999), which was already described in details in section 2.3. KNMI used the RACMO2 (Lenderink et al., 2003), which combines dynamical core of the HIRLAM Numerical Weather Prediction System with the physical parameterization of the European Centre for Medium-range Weather Forecasting used for the ERA-40 re-analysis project. ETHZ used the Climate High Resolution Model (CHRM) RCM described by Vidale et al. (2003). Model performances of the four selected RCMs are analyzed by Jacob et al. (2007) using the simulations of the reference period 1961-1990. Besides the A2 scenario experiments, DMI and ICTP accomplished further experiments using the B2 emission scenario. In addition to these scenarios, A1B is also considered in our analysis: the same climate indices have been determined using the RegCM simulations driven by ECHAM5 GCM (Roeckner et al., 2006).

The simulated trends of the extreme temperature indices are compared in Fig. 5 using the daily temperature outputs of the regional climate modeling experiments (both for the 1961-1990 and the 2071-2100 periods) of four different RCMs. The annual values of the indices are calculated as a spatial average of all the grid points located in Hungary, and then, the projected change is determined. According to the results, negative extremes are estimated to decrease while positive extremes tend to increase significantly. Both imply regional warming in the Carpathian Basin. The largest increase due to this warming trend can be estimated in case of extremely hot days (Tx35GE), hot nights (Tn20GT), hot days (Tx30GE) by more than 100%. In general, the simulated changes are the largest in case of the most pessimistic A2 emission scenario, for instance, the ratio to the changes estimated for the most optimistic B2 is about 1:3. The simulated warming trends of all the temperature indices are completely consistent with the detected trend in the 1961-2001 period (Bartholy & Pongrácz, 2006, 2007).

Table 4 summarizes the projected future trends of the extreme precipitation indices determined using the climate simulations of selected RCMs (i.e., HIRHAM4, RegCM, RACMO2, and CHRM) for the 1961-1990 and the 2071-2100 periods. Estimated changes of annual precipitation indices are generally consistent with the detected trends in the last quarter of the 20th century (Bartholy & Pongrácz, 2005, 2007). However, the projected regional increase or decrease is usually small (not exceeding 20% in absolute value), except

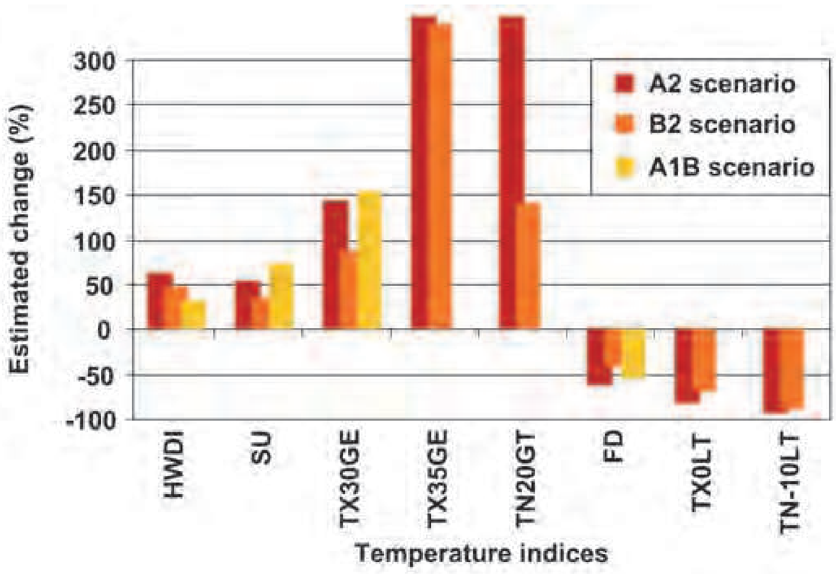

Fig. 5. Projected change of the extreme temperature indices by 2071-2100 based on the daily outputs of the regional climate models HIRHAM, RegCM, RACMO, and CHRM. Reference period: 1961-1990. HWDI is the heat wave duration index defined as for at least 5 consecutive days $T_{max} = T_{max,N} + 5$ °C, where $T_{max,N}$ indicates the mean T_{max} for the baseperiod 1961-1990. SU is the annual number of summer days defined as annual occurrences of $T_{max} \geq 25$ °C. TX30GE is the annual number of hot days defined as annual occurrences of $T_{max} \geq 30$ °C. TX35GE is the annual number of extreme hot days defined as annual occurrences of $T_{max} \geq 35$ °C. TN20GT is the annual number of hot nights defined as annual occurrences of $T_{min} \geq 20$ °C. FD is the annual number of frost days defined as annual occurrences of $T_{min} < 0$ °C. TX0LT is the annual number of winter days defined as annual occurrences of $T_{max} < 0$ °C. TN-10LT is the annual number of severe cold days defined as annual occurrences of $T_{min} < -10$ °C.

Precipitation index	A2			B2			A1B		
	year	January	July	year	January	July	year	January	July
Rx1 (R_{max})	+17%	+29%	–2%	+13%	+23%	–5%	+14%	+13%	+4%
Rx5 ($R_{max,\ 5\ days}$)	+10%	+26%	–11%	+11%	+17%	–11%	+10%	+10%	–5%
SDII (R_{year}/RR1)	+10%	+16%	+13%	+7%	+12%	+1%	+12%	+13%	+10%
RR20 ($R_{day} \geq 20$ mm)	+60%	+233%	+66%	+68%	+212%	–24%	+49%	+69%	+36%
RR10 ($R_{day} \geq 10$ mm)	+14%	+95%	–11%	+20%	+58%	–14%	+22%	+32%	+20%
RR1 ($R_{day} \geq 1$ mm)	–10%	+19%	–31%	–2%	+6%	–19%	–13%	–5%	–25%

Table 4. Projected change of extreme precipitation indices (2071-2100) based on the daily outputs of the regional model HIRHAM, RegCM, RACMO, and CHRM (reference period: 1961-1990). In case of A1B scenario, only RegCM outputs are considered. Rx1 and Rx5 are the largest 1-day and 5-day precipitation totals, respectively. SDII is the simple daily intensity index defined as the ratio of the total precipitation sum and the total number of precipitation days exceeding 1 mm. RR20, RR10, and RR1 are the numbers of precipitation days exceeding 20 mm, 10 mm, and 1 mm, respectively.

of RR20, the number of very heavy precipitation days. Much larger positive and negative changes are projected in January and in July, respectively, on the base of the RCM simulations. These results suggest that the climate tends to be wetter in winter in the Carpathian Basin. The summer precipitation is likely to become less frequent and overall drier but more intense by the end of the 21st century, which is highlighted by the positive estimated changes of SDII (by +13%, +1%, and +10% in case of A2, B2, and A1B scenarios, respectively).

5. Estimated trends of empirical distributions of monthly climate anomalies

Besides the projected future trends of mean values and extreme indices, distributions and empirical probabilities are also analyzed for the period 2071-2100 (compared to 1961-1990, as a reference period) using fine resolution RCM (i.e., PRECIS and RegCM) simulations.
Fig. 6 compares the seasonal projections of monthly anomalies exceeding 4 °C to the observed datasets. In the past, such large monthly anomalies occurred extremely rarely, only in the winter months when the temperature variability is the largest during the year. For the future all simulations project significant increase in the occurrences of these largely warm conditions relative to the past climate.

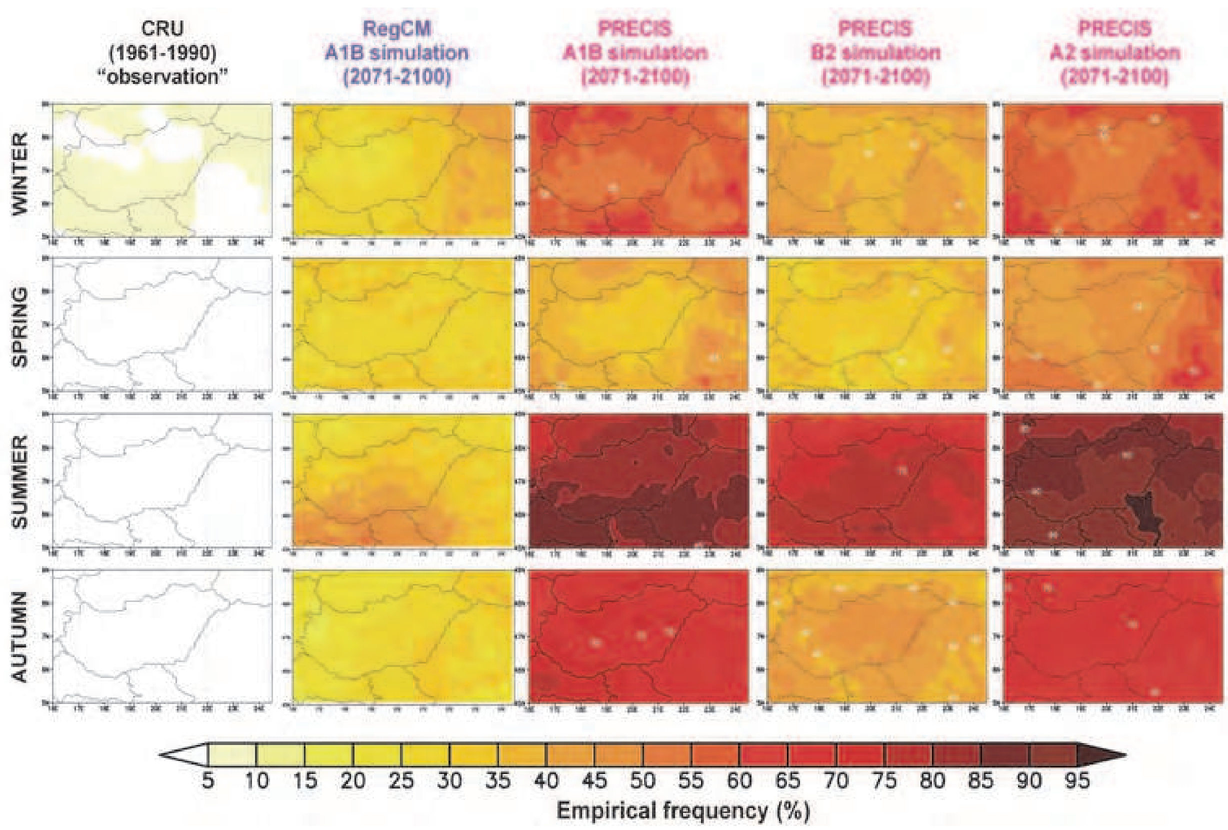

Fig. 6. Projected occurrence of monthly temperature anomalies exceeding +4 °C relative to the 1961-1990 mean values in the four seasons.

Overall, PRECIS simulations suggest larger increase than RegCM simulations, which is in good agreement with the projected mean annual and seasonal warming of the RCMs. In case of all the regional scenarios, summer frequency increase is the largest. PRECIS simulations suggest that the empirical frequency of at least 4 °C monthly temperature anomalies in Hungary exceeds 70%, 80%, and 85%, for B2, A1B, and A2 scenario, respectively.

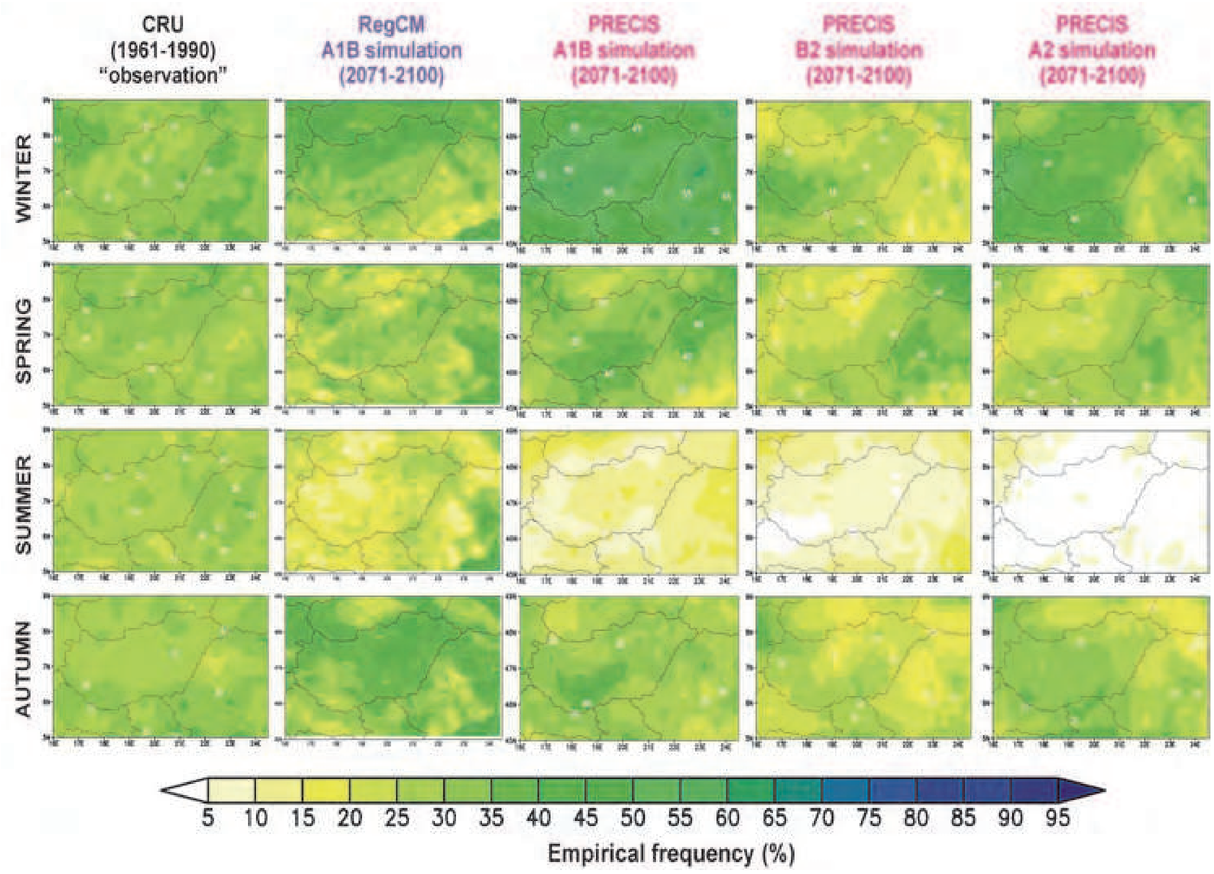

Fig. 7. Projected occurrence of wet monthly precipitation anomalies exceeding +20% relative to the 1961-1990 mean values in the four seasons.

Figs. 7 and 8 compare the seasonal occurrences of monthly precipitation anomalies exceeding +20% (implying wetter than normal climatic conditions) and –20% (implying drier than normal climatic conditions), respectively, to the CRU observations.

Since precipitation has a large variability both in time and space, projected changes in most of the seasons are not significant. Nevertheless, wetter conditions in summer tend to decrease by the end of the 21st century in case of all regional scenarios. In the past, 1961-1990, wet anomalies (shown in Fig. 7) occurred in 25-30% of all the summer months in Hungary. According to the RCM simulations this occurrence will likely to decrease considerably. PRECIS simulations project larger decrease by 2071-2100 than RegCM simulations. RegCM outputs suggest that the empirical frequency is likely to become 10-20% in the western part of the country, whereas 25-30% in the eastern regions. PRECIS simulations suggest that the occurrence frequencies of at least 20% monthly precipitation anomalies in Hungary is not likely to exceed 10%, 15%, and 5%, for B2, A1B, and A2 scenario, respectively.

In the meanwhile, dry climatic conditions (shown in Fig. 8) in summer are likely to occur more often in the future (on the basis of the observations, empirical frequency of monthly precipitation anomalies exceeding –20% is 30-40%). Again, PRECIS simulations suggest larger increase than RegCM simulations. According to the PRECIS outputs, the projected occurrence frequency is likely to at least double by 2071-2100 relative to 1961-1990. Maps on both Fig. 7 and Fig. 8 agree on the future summer drying of the Carpathian Basin, which is also supported by the projected mean precipitation changes (analyzed in section 3.2). In the other seasons, projected occurrence frequency is not likely to change significantly.

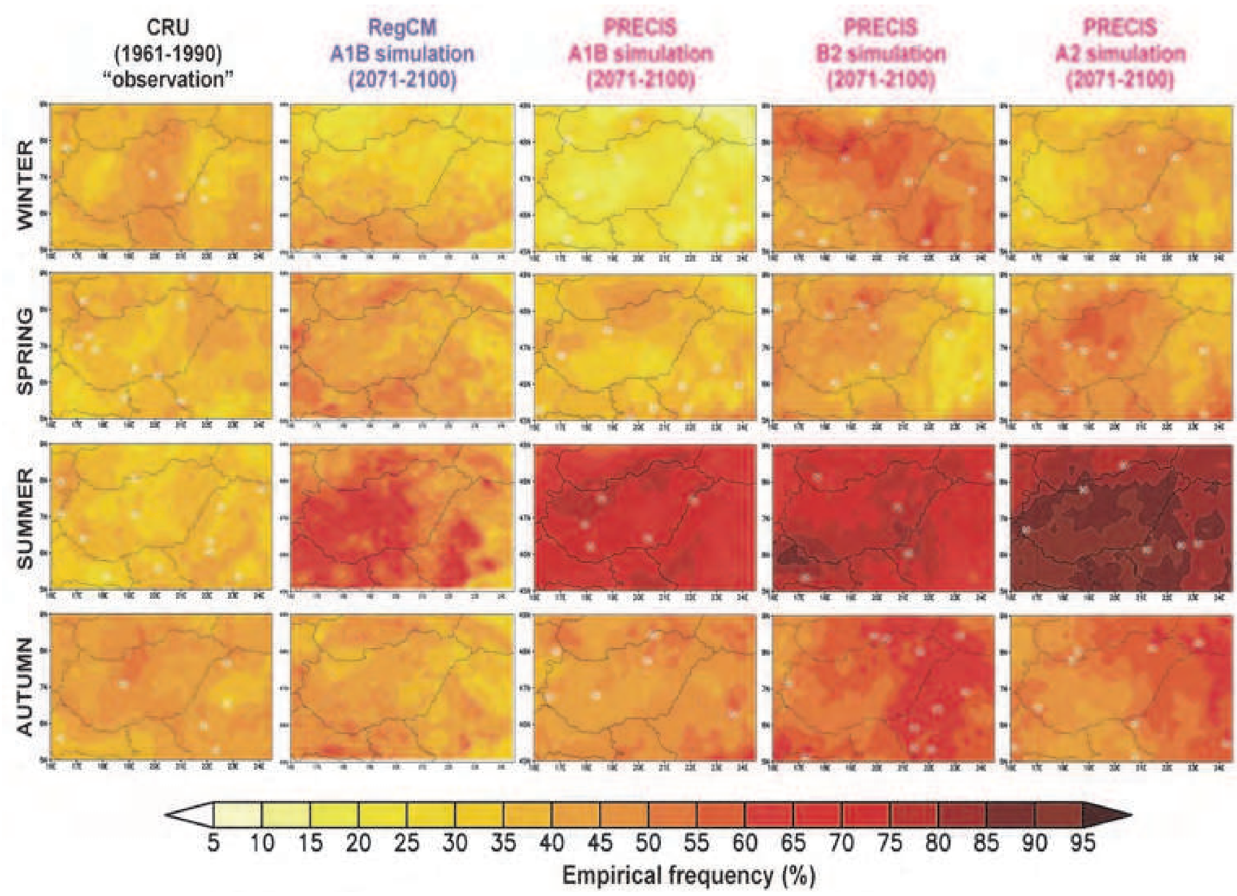

Fig. 8. Projected occurrence of dry monthly precipitation anomalies exceeding –20% relative to the 1961-1990 mean values in the four seasons.

6. Conclusion

Regional climate change trends in the Carpathian Basin (and especially in Hungary) have been assessed in this paper. For this purpose RCM model simulations from PRUDENCE (19 experiments with 50 km horizontal resolution), PRECIS (3 experiments with 25 km horizontal resolution), and RegCM (1 experiment with 10 km horizontal resolution) have been used. Regional consequences of three different emission scenarios have been evaluated, namely, SRES A2, A1B, and B2.

On the basis of the results presented in this paper the following conclusions can be drawn.

1. In the future, the largest mean temperature increase in the Carpathian Basin is likely to occur in summer (3.7-5.1 °C relative to the 1961-1990 reference period). The smallest seasonal increase is simulated in spring (2.7-3.3 °C).
2. The largest warming is estimated for A2 scenario, which is the most pessimistic global emission scenario among the three analyzed here.

3. Opposite changes are projected for seasonal precipitation in the Carpathian Basin. The summer precipitation is very likely to decrease by about 10-33%, whereas winter precipitation tends to increase considerably by 20-37%.
4. In the 1961-1990 reference period, the wettest season was summer, less precipitation was observed in spring and autumn (in this order), and the driest season was winter. RCM simulations projects that the annual distribution of precipitation may be totally restructured resulting in winter/summer becoming the wettest/driest season, which is the opposite of recent climatic conditions.
5. RCM simulations project that the negative temperature extreme indices are likely to decrease in the future, whereas the positive temperature extreme indices tend to increase significantly. Both imply regional warming in the Carpathian Basin.
6. Analysis of precipitation indices suggests that the climate in the Carpathian Basin tends to be wetter in winter. The summer precipitation is likely to become less frequent and overall drier but more intense by the end of the 21st century.
7. The seasonal occurrences of monthly temperature anomalies exceeding +4 °C are projected to increase significantly, the largest changes are estimated in summer (the seasonal occurrences are likely to exceed 70% by 2071-2100).
8. Future summer drying of the Carpathian Basin is very likely. Occurrences of summer monthly precipitation anomalies exceeding +20% (implying wetter than normal climatic conditions) are projected to decrease by 2071-2100 relative to 1961-1990, whereas occurrences of summer monthly precipitation anomalies exceeding –20% (implying drier than normal climatic conditions) are projected to increase.

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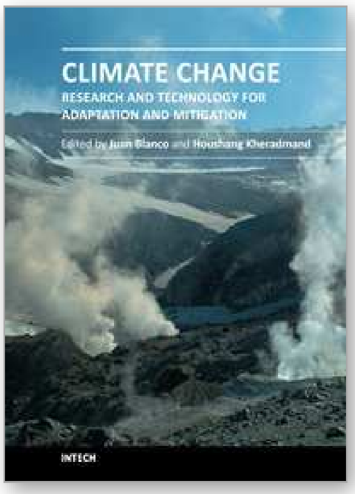

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This book provides an interdisciplinary view of how to prepare the ecological and socio-economic systems to the reality of climate change. Scientifically sound tools are needed to predict its effects on regional, rather than global, scales, as it is the level at which socio-economic plans are designed and natural ecosystem reacts. The first section of this book describes a series of methods and models to downscale the global predictions of climate change, estimate its effects on biophysical systems and monitor the changes as they occur. To reduce the magnitude of these changes, new ways of economic activity must be implemented. The second section of this book explores different options to reduce greenhouse emissions from activities such as forestry, industry and urban development. However, it is becoming increasingly clear that climate change can be minimized, but not avoided, and therefore the socio-economic systems around the world will have to adapt to the new conditions to reduce the adverse impacts to the minimum. The last section of this book explores some options for adaptation.